FAILURE CRITERIA FOR PREDICTION OF TRANSVERSE MATRIX CRACKING IN COMPOSITES

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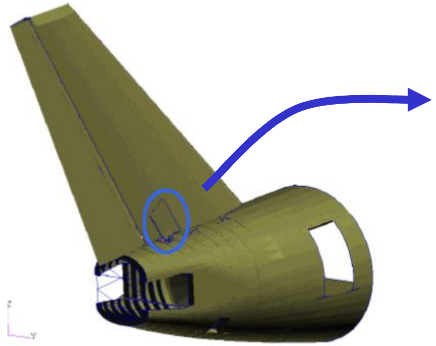
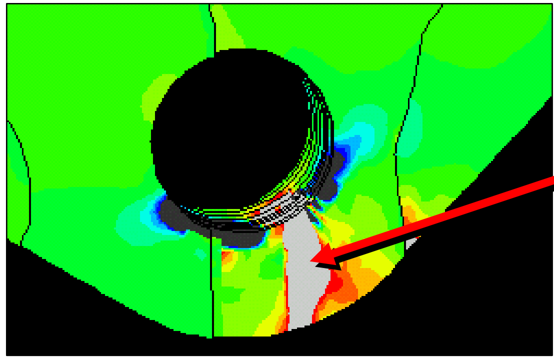
- Approach: slit crack models in composites.
- In-situ strengths.
- Failure criterion for matrix cracking under in-plane shear and transverse tension.
- Validation: comparison with experimental data.
- Conclusions.

Introduction

Failed composite lug



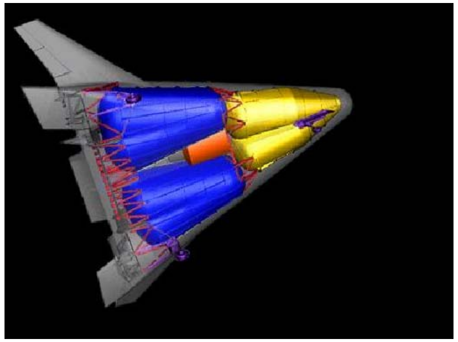


Clevage Fracture

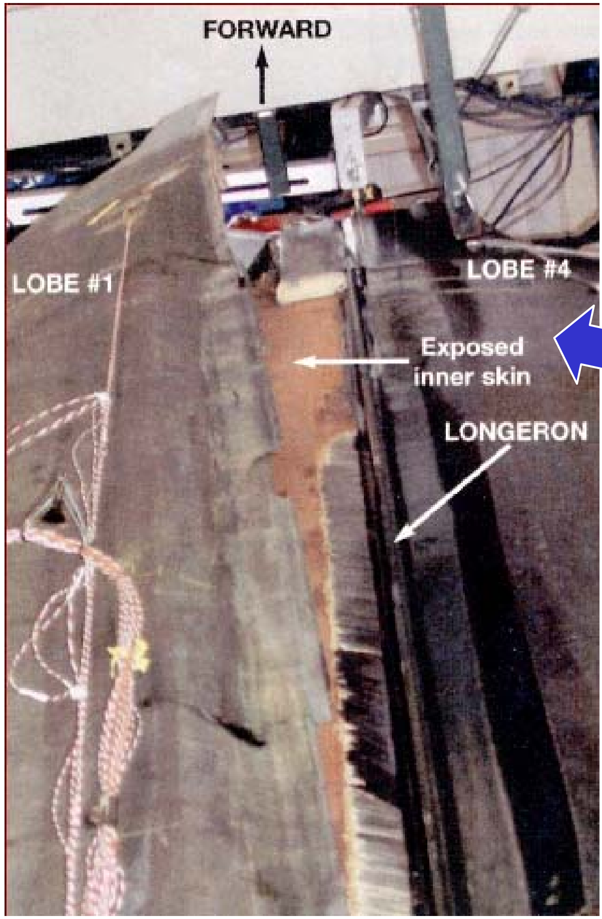
- Failure Criteria are used for predicting damage initiation and, when used in a Continuum Damage Model, final failure.
- Composites have multiple damage modes; each requires a different criterion.
- Failure prediction methodologies and criteria still under debate; main unresolved issues:
  - ✓ in-situ effects.
  - ✓ effects of σ_{12} on fibre kinking.
  - ✓ increase of apparent shear strength under moderate compressive σ_{22}

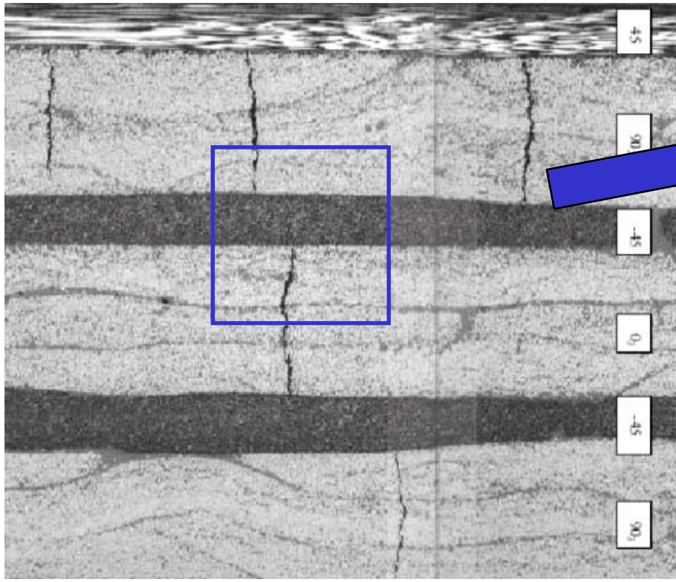
LaRC03 Failure Criteria

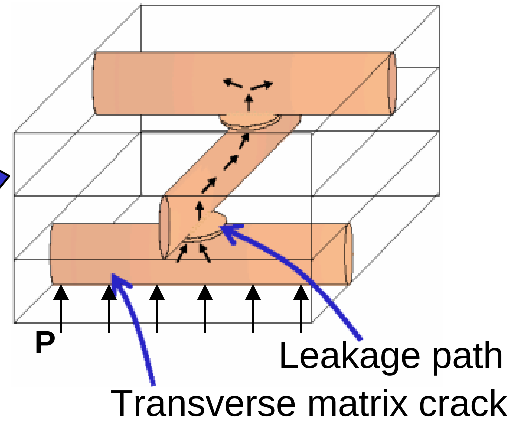
Introduction



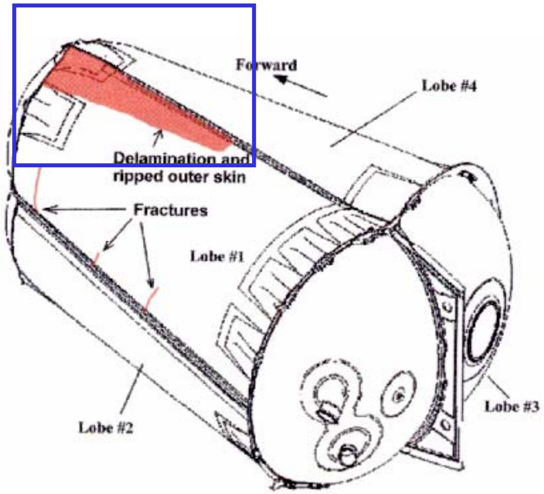
X-33
RLV



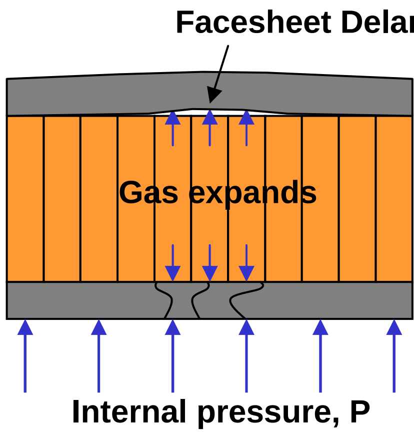




Matrix cracks provide
primary leakage path
in composite tanks



Cryopumping in sandwich core



Tank failed during testing. X-33 Program cancelled by NASA

Introduction

Transverse Tension Matrix Cracking

- Typically considered a benign damage mode
- Important for leakage, damage initiation

Issues/Difficulties Predicting Transverse Matrix Cracks

- In-situ matrix strengths are a function of ply thickness

Typically: $Y_{UD}^{T} \leq Y_{is}^{T} \leq 4Y_{UD}^{T}$ ← tension

$S_{UD}^{L} \leq S_{is}^{L} \leq 4S_{UD}^{L}$ ← shear

UD=unidirectional; is=in-situ

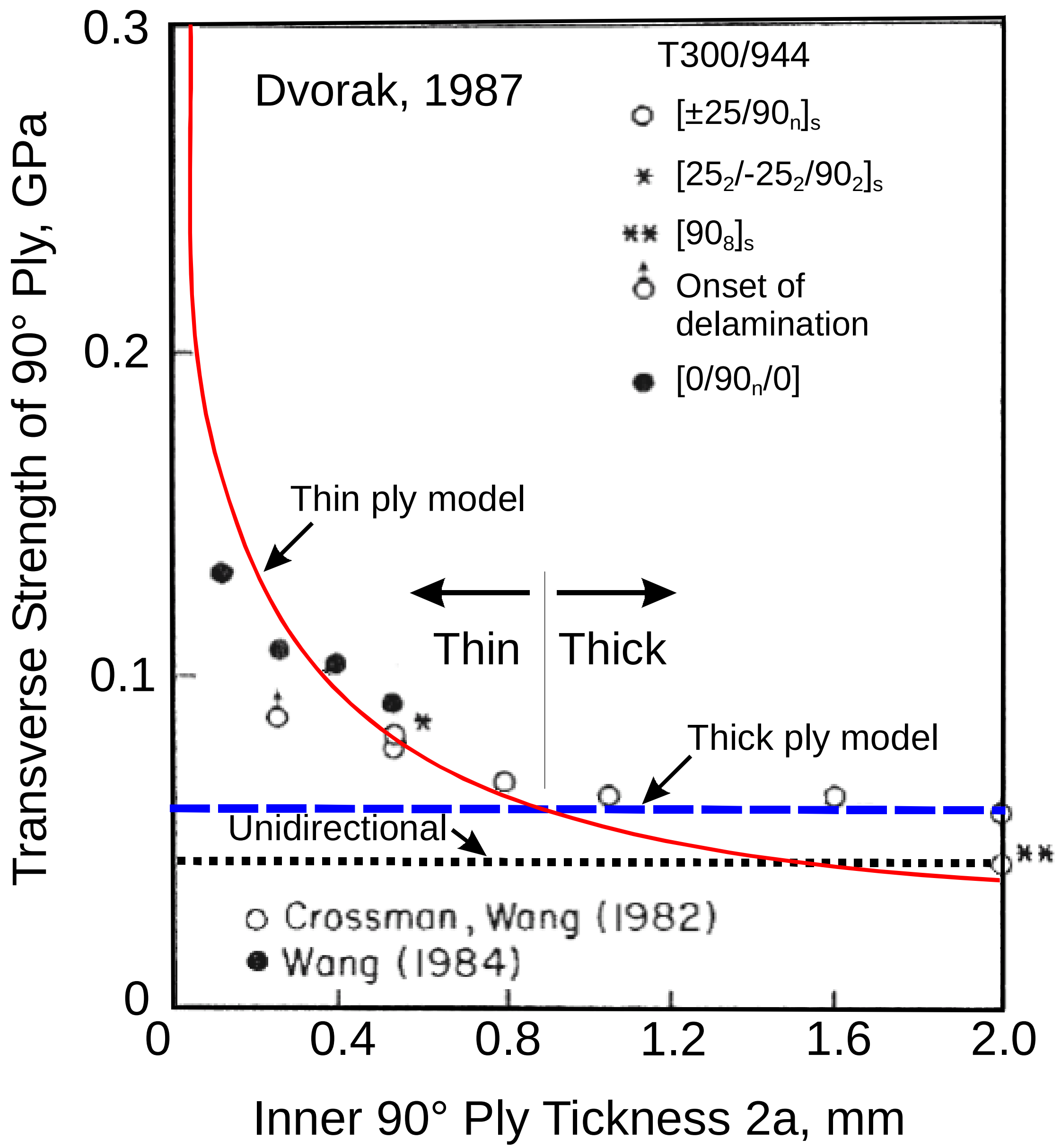
- No fracture mechanics basis in Hashin's criterion

Previous work

- Parvisi, Wang, etc. ('78-'84): identified in-situ effect in tensile tests
- Dvorak, Laws, Tan ('86-'89): fracture mechanics predictions of in-situ strength
- Shahid & Chang ('95): PDCOMP extension of Tan

Introduction

In-situ effect:

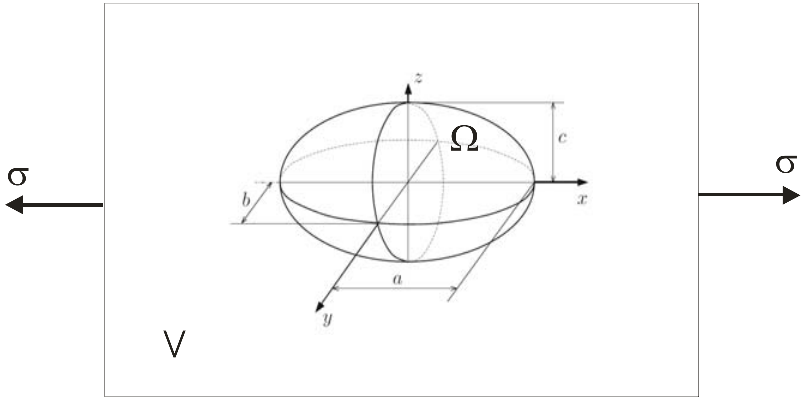


Objectives

- To develop a model able to predict the in-situ strenghts.
- To develop a novel failure criterion for matrix transverse cracking under transverse tension and in-plane shear.
- Validate the models proposed by comparing predictions with experimental data.

Approach

Eshelby's inhomogeneity problem for isotropic materials (1957)



$$C^{V} \neq C^{\Omega}$$ (inhomogeneity)

$$C^{\Omega} \to 0$$ (cavity)

$$c \to \infty; \ \frac{a}{b} \to 0$$ (slit crack)

✓ Elastic field far from inclusion.

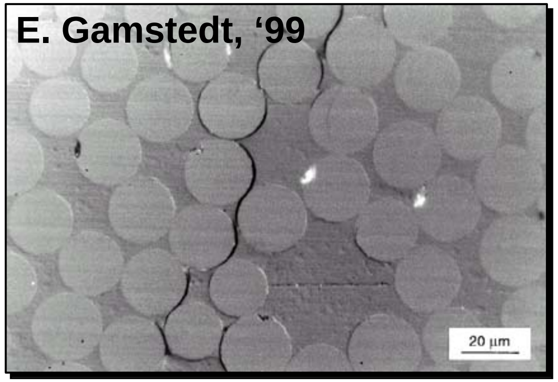
✓ Stress & strain tensors outside the inclusion.

✓ **Interaction energy.**

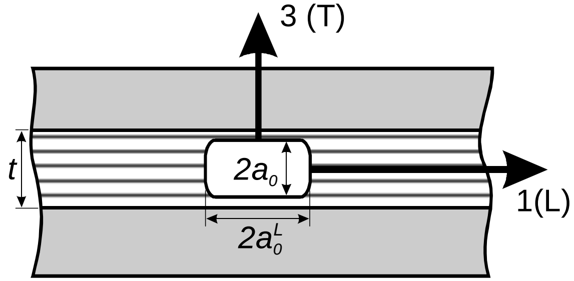
Inhomogeneity problem for orthotropic materials:

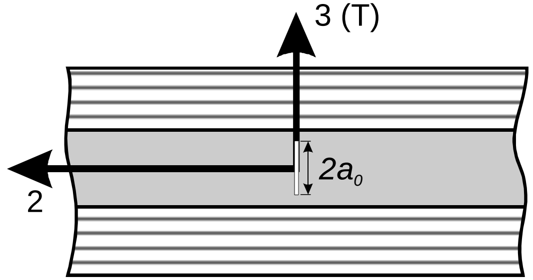
- Kinoshita (1971), Faivre (1971), Laws (1977).

Approach



Material defects can propagate in longitudinal (L) and transverse (T) directions.





$$E_{\text{int}} = \frac{1}{2}\pi a_0\left(\Lambda_{22}^0\sigma_{22}^2 + \chi\left(\gamma_{12}\right)\right)$$

$$\Lambda_{22}^0 = 2\left(\frac{1}{E_2} - \frac{\nu_{21}^2}{E_1}\right)$$

$$\chi\left(\gamma_{12}\right) = 2\int_0^{\gamma_{12}} \sigma_{12}\, d\gamma_{12}$$

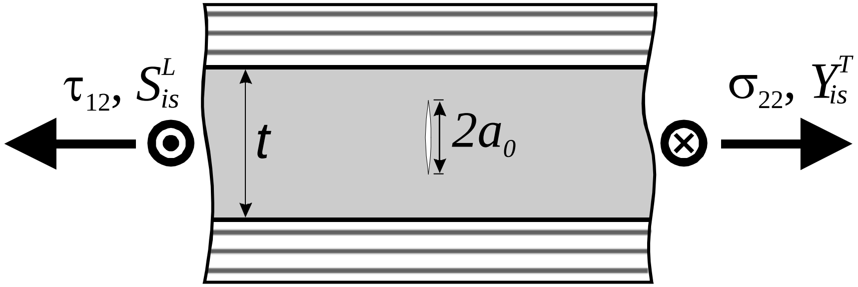
Transverse: unstable growth

$$G(T) = \frac{1}{2}\frac{\partial E_{\text{int}}}{\partial a_0} = \frac{\pi a_0}{2}\left(\Lambda_{22}^0\sigma_{22}^2 + \chi\left(\gamma_{12}\right)\right)$$

Longitudinal: stable growth

$$G(L) = \frac{E_{\text{int}}}{2a_0} = \frac{\pi a_0}{4}\left(\Lambda_{22}^0\sigma_{22}^2 + \chi\left(\gamma_{12}\right)\right)$$

Thick Plies $2a_0 << t$



Transverse Crack Growth

In-situ strengths:

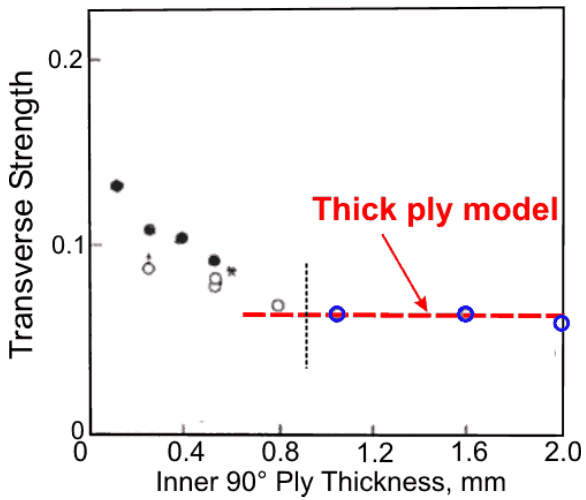
$$G_{Ic}(T) = \frac{\pi a_0}{2} \Lambda_{22}^{0} \left(Y_{is}^{T}\right)^2$$

$$\gamma_{12} = \frac{1}{G_{12}} \sigma_{12} + \beta \sigma_{12}^{3}$$

$$Y_{is}^{T} = \sqrt{\frac{2G_{Ic}(T)}{\pi a_0 \Lambda_{22}^{0}}}$$

$$G_{IIc}(T) = \pi a_0 \int_0^{\gamma_{12}^{u}} \sigma_{12} d\gamma_{12}$$

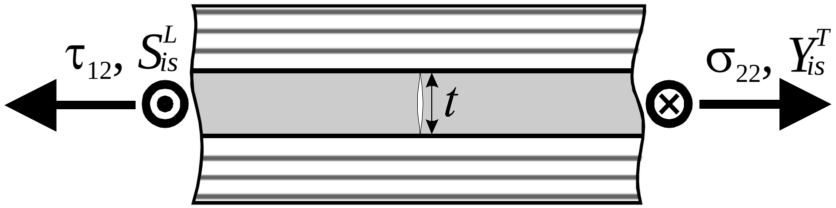
$$G_{IIc}(T) = \pi a_0 \left[\frac{\left(S_L^{is}\right)^2}{2G_{12}} + \frac{3}{4} \beta \left(S_L^{is}\right)^4 \right]$$



Defect size a_0 is assumed to be a material property

In-situ strengths of <u>thick plies</u> are independent of ply thickness t

Thin Plies $2a_0 = t$



Longitudinal crack Growth

In-situ strengths:

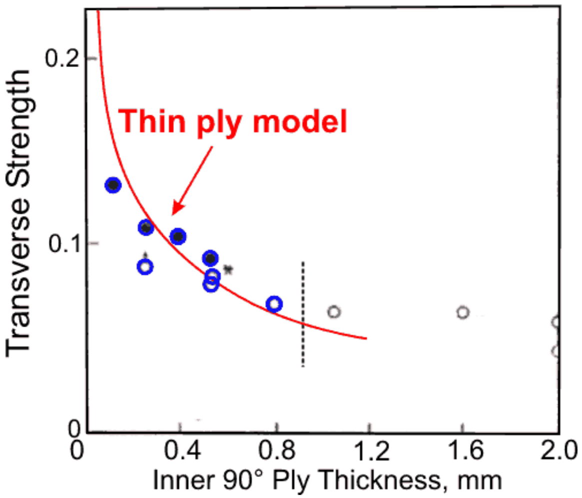
$$G_{Ic}(L) = \frac{\pi t}{8} \Lambda_{22}^{0} \left(Y_{is}^{T}\right)^2$$

$$G_{IIc}(L) = \frac{\pi t}{4} \int_0^{\gamma_{12}^{u}} \sigma_{12} d\gamma_{12}$$

$$\Rightarrow$$

$$Y_{is}^{T} = \sqrt{\frac{8G_{Ic}(L)}{\pi t \Lambda_{22}^{0}}}$$

$$G_{IIc}(L) = \pi t \left[\frac{\left(S_L^{is}\right)^2}{8G_{12}} + \frac{3}{16} \beta \left(S_L^{is}\right)^4 \right]$$

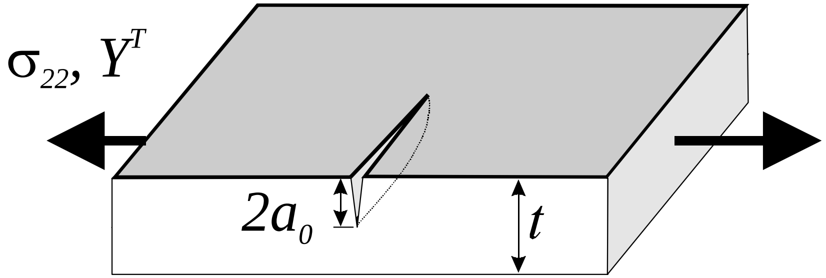


In-situ strengths of <u>thin plies</u>

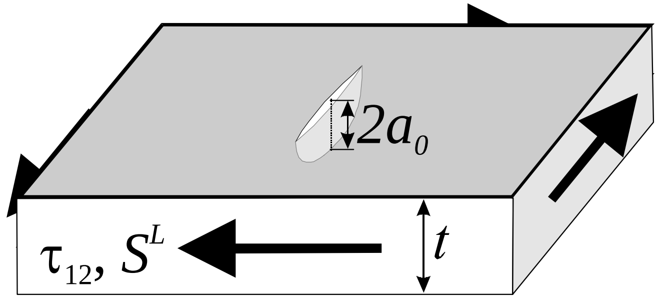
- depend on ply thickness t
- do not depend on defect size a_0

Unidirectional Laminates

Tension test coupon



Shear test coupon



Classic Free Edge Crack Solutions (Tada):

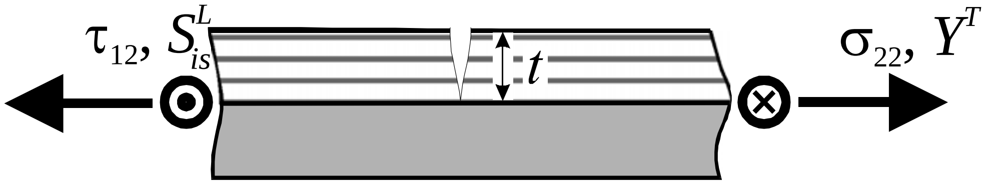
$$G_{Ic}(T) = 1.12^2 \pi a_0 \Lambda_{22}^0 \left(Y^T\right)^2$$

$$G_{IIc}(T) = 2\pi a_0 \int_0^{\gamma_{12}^u} \sigma_{12} d\gamma_{12}$$

Substituting $G_{Ic}(T)$ and $G_{IIc}(T)$ into expressions for thick plies:

$$\begin{cases} Y_{is}^T = 1.12\sqrt{2}\,Y^T \\ \dfrac{\left(S^L\right)^2}{G_{12}} + \dfrac{6}{4}\beta\left(S^L\right)^4 = \dfrac{\left(S_{is}^L\right)^2}{2G_{12}} + \dfrac{3}{4}\beta\left(S_{is}^L\right)^4 \end{cases}$$

Thin Outer Plies $2a_0 = t$



Longitudinal crack growth

Free Edge Crack Solutions (Tada):

$$Y_{is}^{T} = 1.79\sqrt{\frac{G_{Ic}(L)}{\pi t \Lambda_{22}^{0}}}$$

$$\frac{\left(S_{o}^{L}\right)^{2}}{4G_{12}} + \frac{3}{8}\beta\left(S_{o}^{L}\right)^{4} = \frac{G_{IIc}(L)}{\pi t}$$

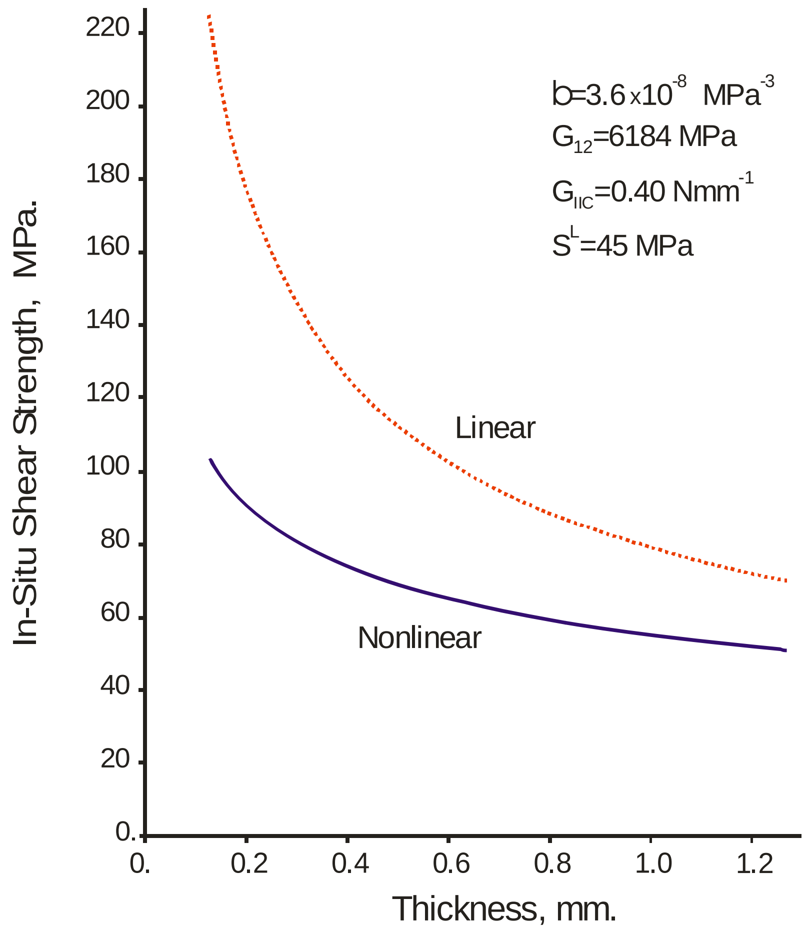
General solution for in-situ shear strengths

$$S_{is}^{L} = \sqrt{\frac{\left(1+\beta\phi G_{12}^{2}\right)^{1/2}-1}{3\beta G_{12}}}$$

Thick ply: $\phi = \frac{12\left(S^{L}\right)^{2}}{G_{12}} + \frac{72}{4}\beta\left(S^{L}\right)^{4}$

Thin ply: $\phi = \frac{48 G_{IIC}}{\pi t}$

Thin outer ply: $\phi = \frac{24 G_{IIC}}{\pi t}$



Mixed-Mode Criterion for Matrix Cracking

Wu and Reuter:

Experimental tests on composite specimens under mode I, mode II and mixed-mode I & II loading.
Fracture surface topography depends on the type of loading.

Hahn Criterion: $$(1-g)\frac{K_I}{K_{Ic}}+g\left(\frac{K_I}{K_{Ic}}\right)^2+\left(\frac{K_{II}}{K_{IIc}}\right)^2\leq 1$$

Using LEFM: $$(1-g)\sqrt{\frac{G_I}{G_{Ic}}}+g\,\frac{G_I}{G_{Ic}}+\frac{G_{II}}{G_{IIc}}\leq 1 \qquad g=\frac{G_{Ic}}{G_{IIc}}$$

Substituting the stresses into the expressions for: $G_I, G_{II}, G_{Ic}, G_{IIc}$

LaRC03 criterion for matrix tensile cracking:

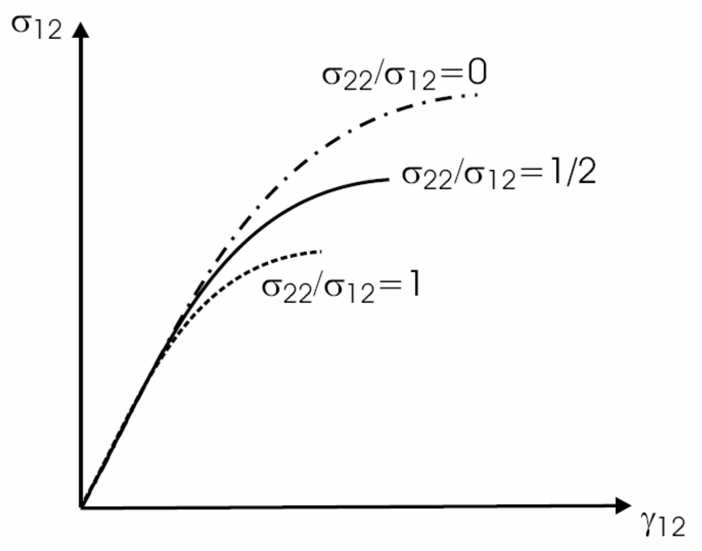
$$\boxed{(1-g)\frac{\sigma_{22}}{Y_{is}^T}+g\left(\frac{\sigma_{22}}{Y_{is}^T}\right)^2+\left(\frac{\sigma_{12}}{S_{is}^L}\right)^2\leq 1}$$

Mixed-Mode Criterion for Matrix Cracking

Non-linear behavior:

LEFM not applicable for relating K to G.

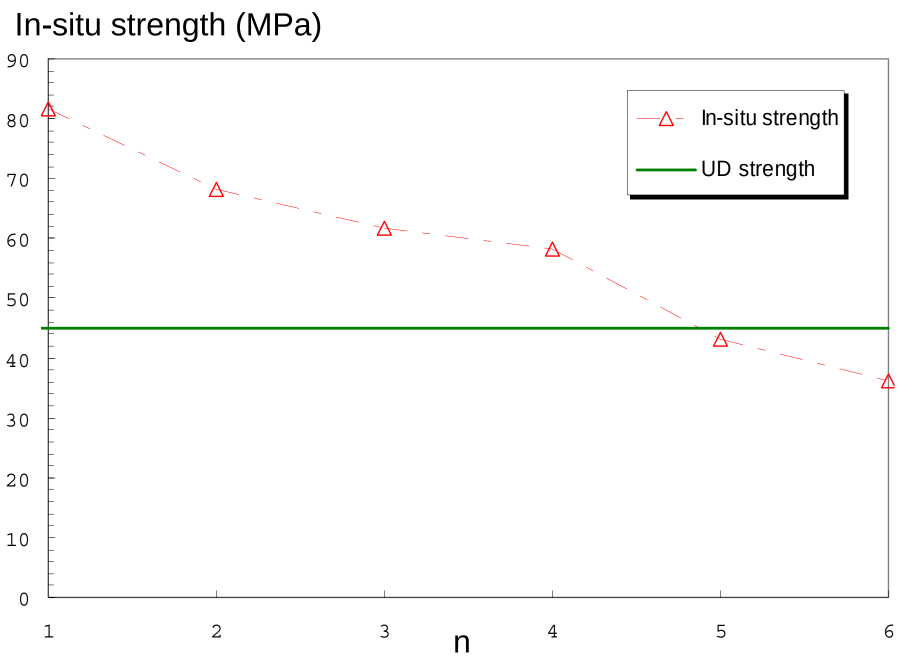
$$\left(1-g\right)\frac{\sigma_{22}}{Y_{is}^{T}}+g\left(\frac{\sigma_{22}}{Y_{is}^{T}}\right)^{2}+\frac{\chi\left(\gamma_{12}\right)}{\chi\left(\gamma_{12}^{u}\right)}\leq 1$$

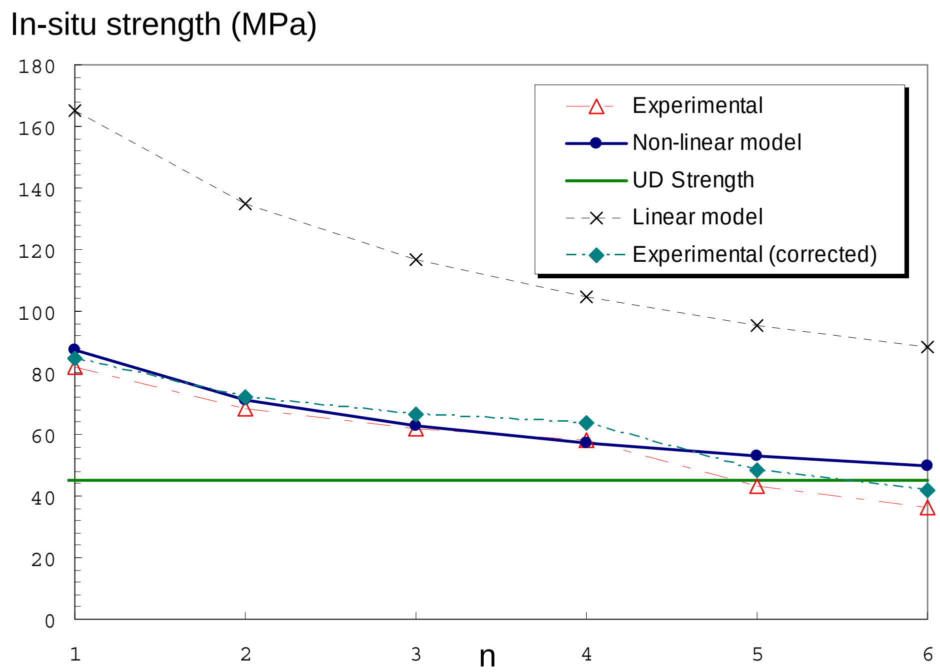


Verification Problems

CASE 1: In-situ shear strength

Chang and Chen experiments in $(0_n/90_n)_s$ CFRP laminates (1987).





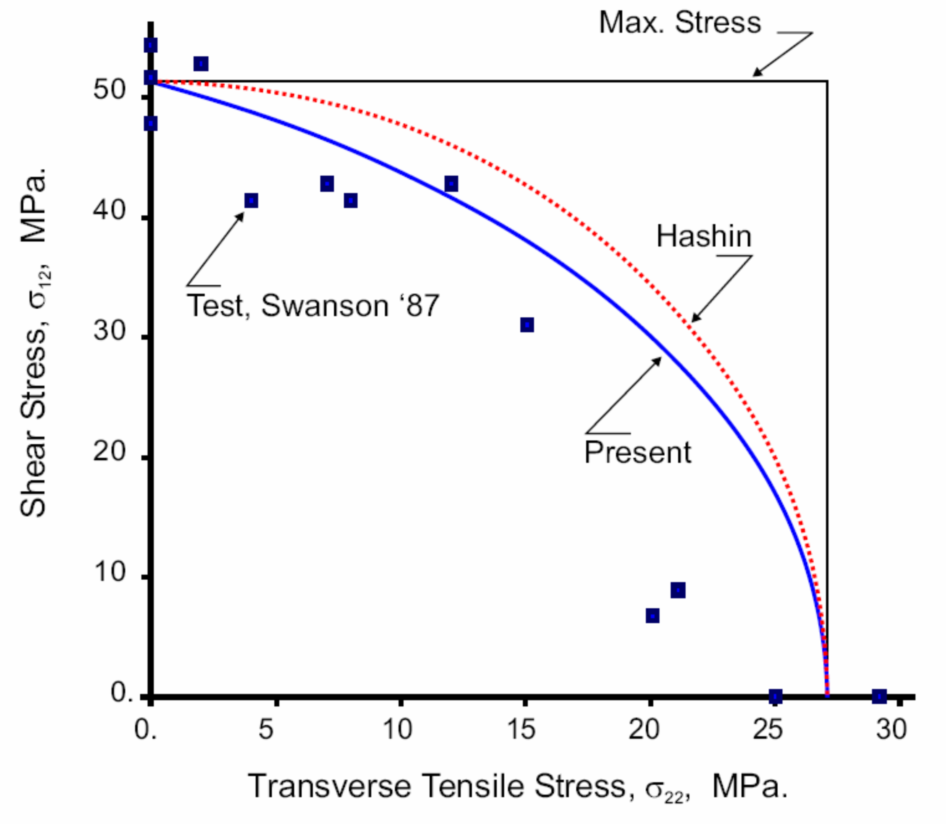
Verification Problems

CASE 2: New failure criterion applied to unidirectional laminates

Experimental data:

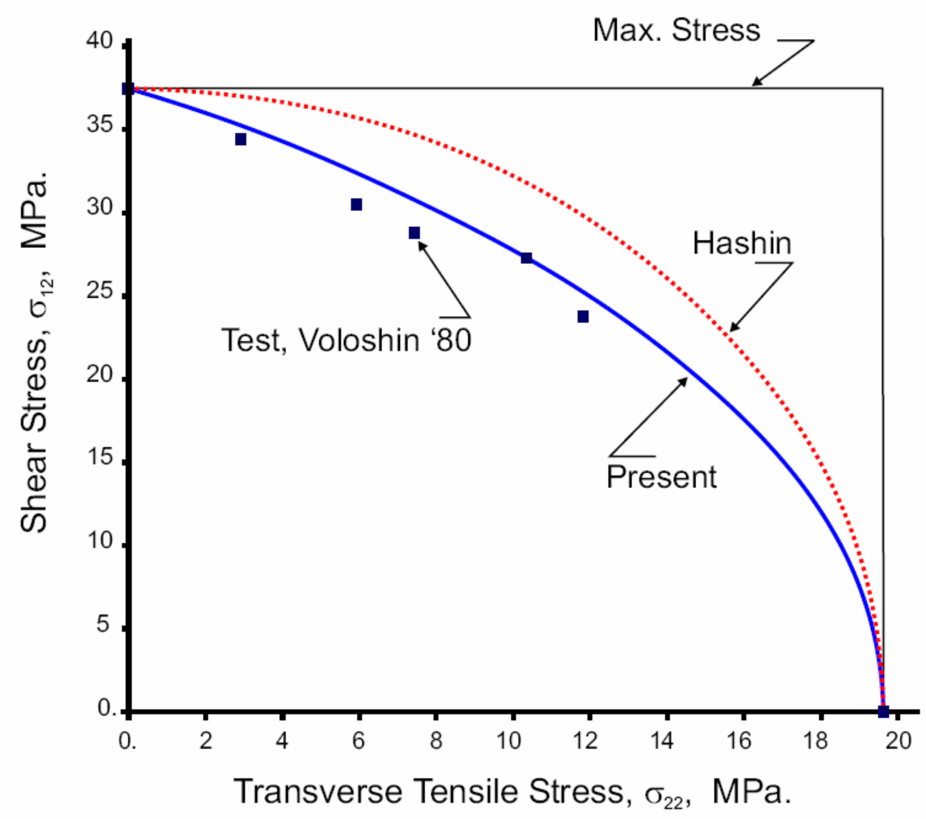
- AS4-55A, Swanson (1987).
- E-glass-LY556, Soden (1998).
- Scotchply, Voloshin (1980).

AS4-55A

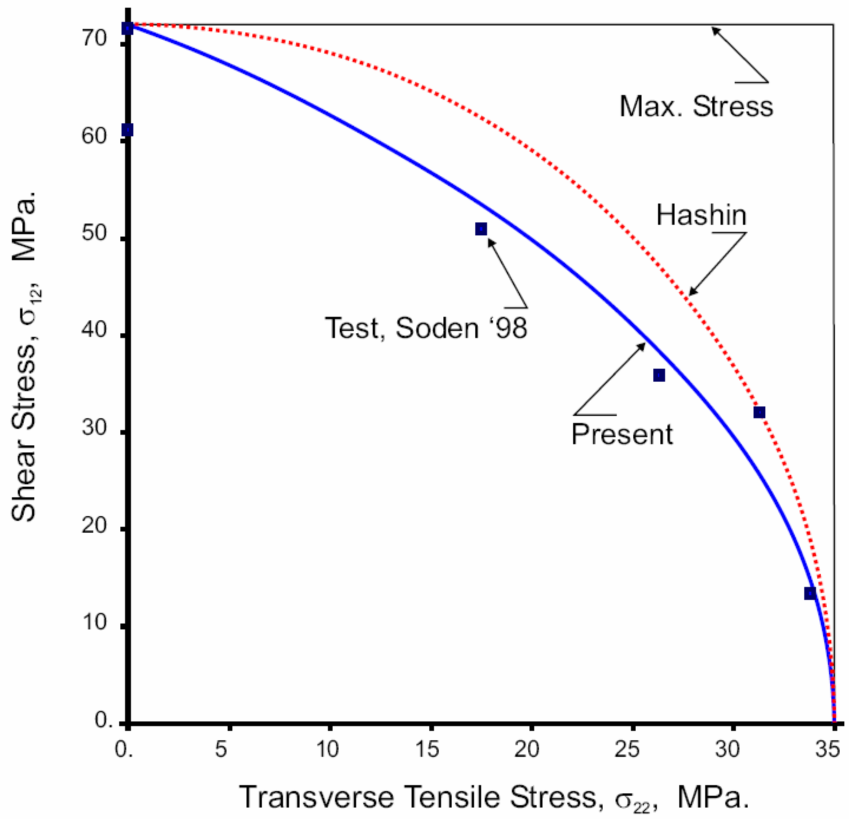


Verification Problems

Scotchply



E-glass-LY556



Conclusions

Conclusions

- New model, based on non-linear shear behavior, was developed for the prediction in-situ shear strengths.
- New criterion for tensile matrix cracking developed based on ply-level fracture mechanisms.
- New criterion uses easily measured unidirectional strength properties and ply configuration to calculate in-situ strengths.
- Predictions are in excellent correlation with experimental results.